INVESTIGATIONS OF THE ELECTRICAL BREAKDOWN PROPERTIES OF INSULATOR MATERIALS USED IN HIGH VOLTAGE VACUUM DIODES*

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Abstract

The Injector for the proposed Dual-Axis Radiographic Hydrodynamic Testing (DARHT) Facility at Los Alamos utilizes a monolithic insulator deployed in a radial configuration [1]. The 1.83-m-diam x 25.4-cm-thick insulator with embedded grading rings separates the output oil transmission line from the vacuum vessel that contains the re-entrant anode and cathode assemblies. Although much work has been done by the pulse power community in studying surface flash-over of insulating materials used in both axial and radial configurations, dendrite growth at the roots of grading rings embedded in materials suitable for very large insulators is less well characterized. Degradation of several acrylic insulators has been observed in the form of dendrites growing at the roots of the grading rings for large numbers (100's) of pulses on the prototype DARHT Injector and other machines using similar radial geometries. In a few cases, these dendrites have led to catastrophic bulk breakdown of the acrylic between two grading rings making the insulator a costly loss. Insulating materials under investigation are acrylic (Lucite), epoxy (Furane), and cross-linked polystyrene (Rexolite); each of these materials has its own particular mechanical and electrical merits. All of these materials have been cast and machined into the required large size for the Injector. Test methods and the results of investigations into the breakdown strength of various interface geometries and the susceptibility of these materials to dendrite growth are reported.

Introduction

The DARHT Injector was historically designed to utilize a 1.83-m-diam x 25.4-cm-thick acrylic insulator with embedded 9.53-mm-thick grading rings to separate the output oil transmission line from the vacuum vessel that contains the re-entrant anode and cathode assemblies. The injector pulsed power system was designed to be repeatable and to reliably produce a 4 MV$\pm$1%, 65 ns flat-top pulse with a rise and fall time of about 20 ns [2,3]. After extensive testing, modifications, and circuit modeling [4], the injector has met all of its specifications except for the high-voltage reliability of the radial insulator. Figure 1 is an equipotential plot for this insulator from the electromagnetic field solver Flux2D [5].

After 10's to 100's of pulses at 3- to 4-MV during early injector testing, inspection of the acrylic insulator revealed dendrites emanating from the roots of the grading rings. These dendrites grew both outward toward the outer conductor and inward toward the cathode suggesting a bipolar breakdown phenomena. Continued pulsing at the higher voltages led to dielectric breakdown with the result being a carbonized arc track in the plastic between the roots of adjacent grading rings; this made the insulator a costly and total loss. Since no failures of this type had occurred in the acrylic insulator of the REX Injector [1], a program was initiated to review the electrical and mechanical design stresses. This effort included exploring alternate insulator materials complemented by scaled high voltage tests of samples in various configurations mocking up the grading ring root interfaces.

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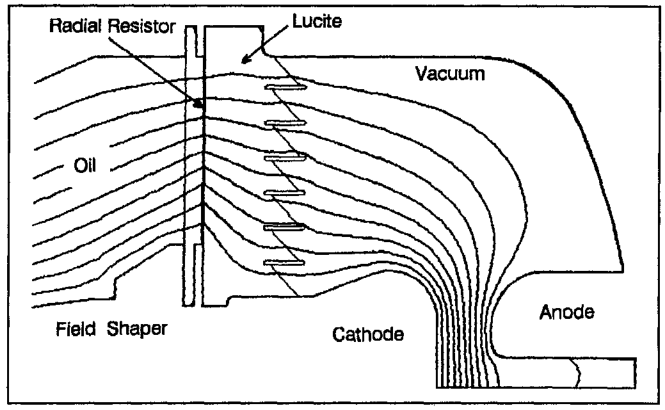

Figure 1. Insulator/Diode equipotential plot.

An obvious difference between the REX and DARHT prototype Injector systems was the bipolar and late time positive postpulse of the latter. Figure 2 is a trace of this bipolar pulse as recorded by a 500 MHz digitizer reading an E-dot probe located in the oil region behind the radial insulator; the pulse promptly reverses and remains positive for relatively long times. One consequence of this pulse reversal is that the outer spool piece (ground) that holds the insulator could become an electron emitter where the field is enhanced in the gap between the two parts. Our test program was designed to investigate these, and other, polarity and geometry effects, as well as the material factors affecting breakdown.

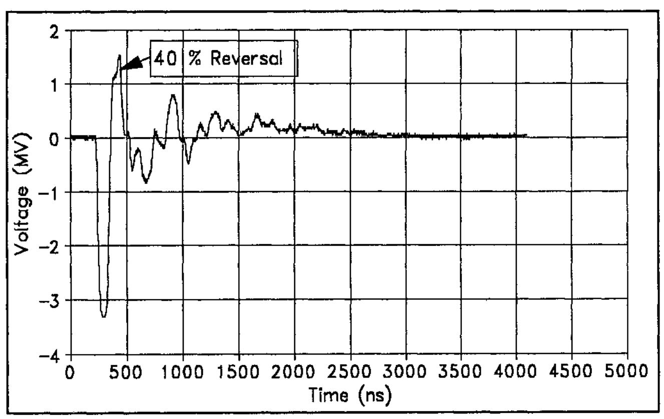

Figure 2. Bipolar pulse of DARHT prototype Injector.

Insulator Materials

Although the first insulators for REX and several for the present injector were an acrylic polymer resin cast by Reynolds Polymer Technologies Inc, Santa Ana, CA, an epoxy based insulator has recently survived greater than 7000 shots before failure between the outer grading ring and the grounded spool piece. This insulator was cast for Los Alamos by Physics International Company, San Leandro, CA and is made of an epoxy

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14. ABSTRACT

The Injector for the proposed Dual-Axis Radiographic Hydrodynamic Testing (DARHT) Facility at Los Alamos utilizes a monolithic insulator deployed in a radial configuration [1]. The 1.83-m-diam x 25.4-cm-thick insulator with embedded grading rings separates the output oil transmission line from the vacuum vessel that contains the re-entrant anode and cathode assemblies. Although much work has been done by the pulse power community in studying surface flash-over of insulating materials used in both axial and radial configurations, dendrite growth at the roots of grading rings embedded in materials suitable for very large insulators is less well characterized. Degradation of several acrylic insulators has been observed in the form of dendrites growing at the roots of the grading rings for large numbers (lOO's) of pulses on the prototype DARHT Injector and other machines using similar radial geometries. In a few cases, these dendrites have led to catastrophic bulk breakdown of the acrylic between two grading rings making the insulator a costly loss. Insulating materials under investigation are acrylic (Lucite), epoxy (Furane), and cross-linked polystyrene (Rexolite); each of these materials has its own particular mechanical and electrical merits. All of these materials have been cast and machined into the required large size for the Injector. Test methods and the results of investigations into the breakdown strength of various interface geometries and the susceptibility of these materials to dendrite growth are reported.

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resin known as Furane (EPOCAST 202A/D40) supplied by Furane Products Company, Los Angeles, CA. The epoxy insulator was used without wiping the surfaces with silicone oil as is the normal practice in high energy pulsed diode machines. The oil coating is applied so that in the event of a surface flash-over, the arc will diffuse over the surface of the insulator allowing for easy removal of any debris by polishing. As will be presented under Results, the presence of oil at the grading ring interfaces greatly reduces the breakdown strength of the insulator material, especially for positive polarity pulses. The recent long life of the epoxy insulator is mainly attributable to the absence of oil. This insulator also had thicker (19.05 mm) grading rings which reduced the root stress by 10 percent and better preparation of material surfaces, particularly at interfaces. The recent epoxy failure is thought to be due to enhanced field stress combined with electron emission across the nominal 0.75 mm clearance gap for positive polarity reversal between the outer spool piece and the insulator. Recently, Los Alamos has acquired insulators made of cross-linked polystyrene (Rexolite 1422) which were cast by C-Lec Plastics, Palmyra, NJ; these are the largest pieces of Rexolite ever cast. The advantages of Rexolite are its easy machining without annealing and its low dielectric constant which reduces any enhanced field stress. Table 1 lists some of the typical properties of the above mentioned candidate insulator materials [6,7,8].

Table 1. Important Material Properties for Insulators

	Acrylic	Rexolite	Furane
Tensile Strength (psi)	>7000	7000	6300
Dielectric Constant (@1MHz)	2.75	2.53	3.80
Dissipation Factor(@1MHz)	0.016	0.00012	0.034
Volume Resistivity (Ω-cm)	10^{13}-10^{14}	10^{16}	$>10^{13}$
ASTM (0.125", Volts/mil)	400-500	500	350

Although a brief review of the properties given in Table 1 could imply that Rexolite is the best and Furane epoxy is the worst material for the radial insulator application, many other requirements must be met. One important requirement is that the insulator be repairable after a failure; the acrylic insulators were not able to be repaired by Reynolds Polymer using either parent material or cement type fills whereas the recently failed Furane epoxy insulator was repaired by a standard patch fill technique developed by Physics International. Small repairs of Rexolite have been accomplished by C-Lec Plastics but the success of the larger volume repairs required for these type of failures has not yet been demonstrated. These three materials became the subjects for the high-voltage breakdown strength test program as described in the next section.

Experimental Test Setup

A set of tests was designed to determine the ultimate breakdown strength of the dielectric materials of interest for three geometries that are representative of the interference fit of the grading rings in the acrylic insulators. As shown in Figure 3, each standard sample consists of an electrode with a 1.157 mm radius tip supported by a shoulder that provides a controlled gap (0.038- to 0.051-mm) between the electrode and the sample. These three cases are: (1) an air gap, (2) a silicone oil gap, and (3) a high conductivity solution in the gap to simulate a perfect fit of the electrode with the sample. The three sample types of acrylic, Furane epoxy, and Rexolite were all machined from bulk cast blanks to the desired envelope dimensions. The electrode "well" was then carefully bored with special tools in two separate machining steps to ensure near exact uniformity between samples. Following this machining process, the samples were washed with an Alconox soap solution and rinsed with distilled water. The electrodes (one per sample) were made with a numerically controlled machine from 6061 aluminum rod stock and then carefully hand finished to remove any tool marks. These were then cleaned with Freon and rinsed with distilled water. The final step was the inspection of the surface finish under a microscope where each electrode was compared to a "standard".

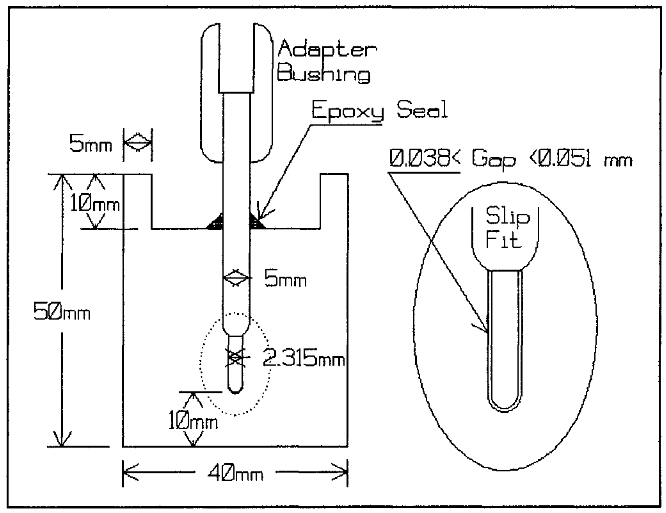

Figure 3. CADD drawing of the standard sample with electrode.

The design of this standard sample utilizes a geometry that stresses a reasonable volume of material wherein the fields can be calculated for the nominal 10 mm sample thickness as shown in Fig. 4. The field from the tip of the electrode to the ground plane for all three samples for the gap either filled with oil or high conductivity water is about 600 kV/cm for each 100 kV of applied voltage pulse. In the case where the gap is air, the field in the air gap is enhanced by the ratio of the dielectric constants causing the field to be reduced in the bulk to 555 kV/cm for acrylic or Rexolite and 525 kV/cm for Furane epoxy. The field enhancement of the sample geometry is about midway between that of the ball-plane and logarithmic case which give 870- and 380-kV/cm for an applied voltage of 100 kV, respectively [9].

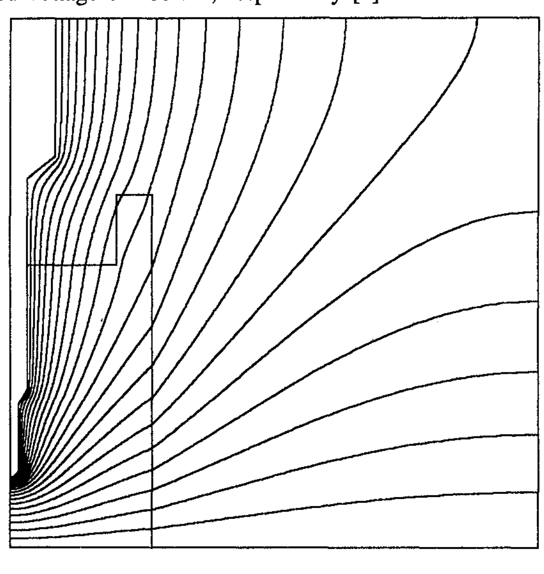

Figure 4. Equipotential plot for Furane epoxy sample.

The test set-up was configured to operate in the ambient laboratory environment rather than vacuum to facilitate the rapid exchange of test samples; therefore, the fixture that held the three test samples was immersed in transformer oil to prevent surface flash-over. This required that the individual sample electrodes be sealed where the electrode entered the sample to preserve the conditions in the gap as shown in Fig. 3. Figure 5 shows the fixture that allows the simultaneous pulsing of the three different materials each in the same gap configuration which insures that a qualitative comparison can be made. The test fixture was driven by an 11-stage, 275-ohm, cable pulser, known locally as the Femcor (Field Emission Corp., McMinnville, OR), which is can of produce a 550-kV, 180-ns (FWHM) pulse into a matched load. The pulser normally delivers a negative pulse which is reproducible within a few percent and very similar in shape to that of the DARHT Injector as shown in Fig. 6. Positive polarities were obtained by reversing the pulser feed and ground to a floating field toroid that held the test fixture. Figure 6 also shows the result of a sample that has broken down at a very low field and the more typical breakdown on the flat portion of the pulse.

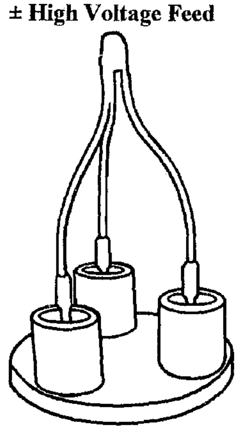

Figure 5. Fixture for simultaneous testing of three samples.

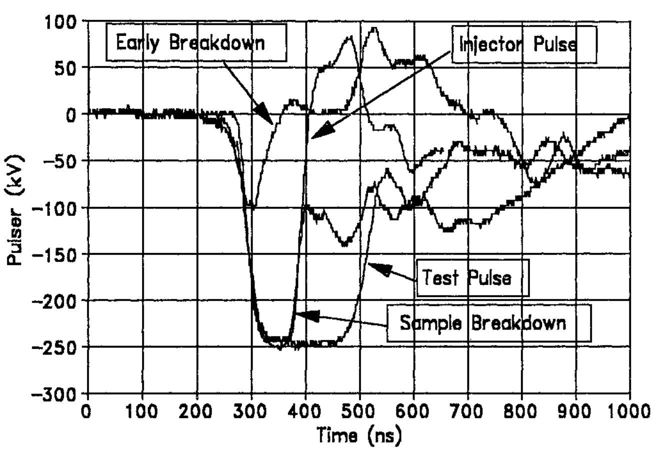

Figure 6. Femcor pulser waveforms used to test samples.

The pulsed voltage applied to a sample set started well below the anticipated breakdown field for the weakest sample; twenty pulses were delivered before increasing the voltage in steps of about 10 percent. Once a sample failed, it was replaced with a "dummy" sample that had a much less field enhanced electrode; the test was continued until each of the original samples had failed. A typical set of data using this procedure is given in Table 2.

Table 2. Typical Set of Sample Breakdown Data

Breakdown Data using Femcor Pulser
Date: 2/19/93
Sample Details: 3/32" diam electrodes
with 0.002" air gap

			Peak Field in Bulk	
Voltage kV	Number Pulses	Acrylic kV/cm	Epoxy kV/cm	Rexolite kV/cm
236	20	1310	1239	1310
259	20	1437	1360	1437
288	20	1598	1512	1598
324	20	1798	1701	1798
344	20	1909	1806	1909
364	20	2020	1911	2020
388	20	2153	2037	2153
412	20	2287	2163	2287
447	6	2481B	2347	2481
432	1		2268B	2398
432	20			2398
455	20			2525
464	20			2575
491	20			2725
524	11			2908B

Results

Tables 3 and 4 present summaries of the negative and positive polarity tests, respectively. In some cases, the samples withstood the highest voltage achieved during a given test sequence; these data are indicated by a (>) symbol and others that failed at an unexplained low voltage are marked with a (*). Each data column in the tables gives the average field across the 10 mm sample; the bottom entry is the maximum field in the dielectric. The results marked with a (*) are not included in these calculations.

Table 3. Negative Polarity Data in kV Across Sample

	Air Gap	Oil Gap	No Gap
Acrylic	>459 456 447 *223 2520 kV/cm	>450 392 344 335 318 300 2140 kV/cm	663 >575 >513 3500 kV/cm
Furane Epoxy	493 >459 432 432 2385 kV/cm	335 297 272 243 238 235 1620 kV/cm	556 525 469 3100 kV/cm
Rexolite	524 453 450 *308 2640 kV/cm	493 452 405 392 369 2535 kV/cm	>663 >638 >513 3630 kV/cm

Table 4. Positive Polarity Data in kV Across Sample

	Air Gap	Oil Gap	No Gap
Acrylic	437 530 >568 2840 kV/cm	213 244 255 256 1450 kV/cm	523 >525 3145 kV/cm
Furane Epoxy	436 442 460 2340 kV/cm	244 255 256 319 1610 kV/cm	500 >523 3070 kV/cm
Rexolite	416 463 506 2560 kV/cm	378 >384 390 391 2315 kV/cm	>523 >525 3145 kV/cm

A review of both the negative and positive polarity field data clearly indicates that the addition of oil in the gap leads to a significant reduction in the effective breakdown strength of the acrylic and Furane epoxy samples. It is thought that the high fields in the gap cause the oil to form streamers which are then readily coupled into the dielectric material leading to failure. The cross-linked nature of Rexolite apparently makes it more resistant to this effect. The data indicate that the only polarity dependent material is acrylic for the case of oil in the gap. The Furane epoxy had the lowest breakdown strength in all cases which is in agreement with the ASTM data given in Table 1. The intrinsic breakdown strength of Rexolite was not capable of being determined at the highest output voltages of the pulser; samples with a stressed area less than the 10 mm used in these experiments are being fabricated to complete this study.

Conclusions

The test results have consistently shown that using oil in a narrow gap leads to reduced breakdown strength due to streamer formation that readily couples into the insulator material. Positive polarity slightly reduces the breakdown strength of all materials. Rexolite has the highest breakdown strength under all conditions and would have the additional benefits of reduced field enhancement at triple points due to its lower dielectric constant. Although epoxy (Furane) appears to have the lowest breakdown strength of the three materials, it has the advantages of a short manufacturing cycle and is repairable. The high dielectric constant of epoxy is a disadvantage due to enhanced stresses at vacuum/metal interfaces. Acrylic has been eliminated for further use as an insulator due to its complicated manufacturing and machining cycles and its apparent susceptibility to dendrite growth. Additional experiments are underway with larger electrode gap spacings which are more typical of the present fit of the grading rings to the insulator.

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References

[1] R.L. Carlson et al, "'REX' A 5-Megavolt Pulsed-Power Source for Driving High-Brightness Electron Beam Diodes," proceedings of the *1991 IEEE Pulsed Power Conference*, pp 82- 85.

[2] J.N. Downing et al, "Pulsed Power Systems for the DARHT Accelerators," proceedings of the *1991 IEEE Pulsed Power Conference*, pp 949-952.

[3] J. Fockler, et al, "A 4 MV±1% Flat-Top Electron Diode Driver," proceedings of the *1991 IEEE Pulsed Power Conference*, pp 177-182.

[4] J.G. Melton "Circuit Modeling and Component Trimming to Achieve Performance Requirements for the DARHT Prototype Injector," in these proceedings.

[5] FLUX2D Version 6.51, Magsoft Corp., Troy, New York.

[6] F.M. Clark, Insulating Materials for Design and Engineering Practice, John Wiley and Sons, Inc., New York, 1962.

[7] Technical Bulletin EP-70-49-A-4, Furane Plastics, Inc., Los Angeles, California.

[8] Technical Bulletin S-266A, American ENKA Corp., Brand-REX Division, Willimantic, Connecticut.

[9] E.Kuffel and W.S. Zaengl, High Voltage Engineering Fundamentals, Pergamon Press, New York, 1984, Chap. 4.